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Prescribed by ANSI Std. 239.18

1 separate items enclosed

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MEMORANDUM FOR PRS (In-House Publication)

FROM: PROI (STINFO) 18 June 2002

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-VG-2002-152**
Greg Spanjers (PRSS) et al., "Herriott Cell Augmentation of a Quadrature Heterodyne Interferometer" (viewgraphs only)

AIAA JPC **(Statement A)**
(Indianapolis, IN, 07-10 July 2002) (Deadline = 30 June 2002)

1. This request has been reviewed by the Foreign Disclosure Office for: a.) appropriateness of distribution statement, b.) military/national critical technology, c.) export controls or distribution restrictions, d.) appropriateness for release to a foreign nation, and e.) technical sensitivity and/or economic sensitivity.
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Comments:____________________

APPROVED/APPROVED AS AMENDED/DISAPPROVED

____

PHILIP A. KESSEL Date
Technical Advisor
Space and Missile Propulsion Division

20021119 160

Herriott Cell Augmentation of a Quadrature Heterodyne Interferometer

Erik L. Antonsen
Rodney L. Burton
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AFRL Propulsion Directorate
Edwards AFB, CA

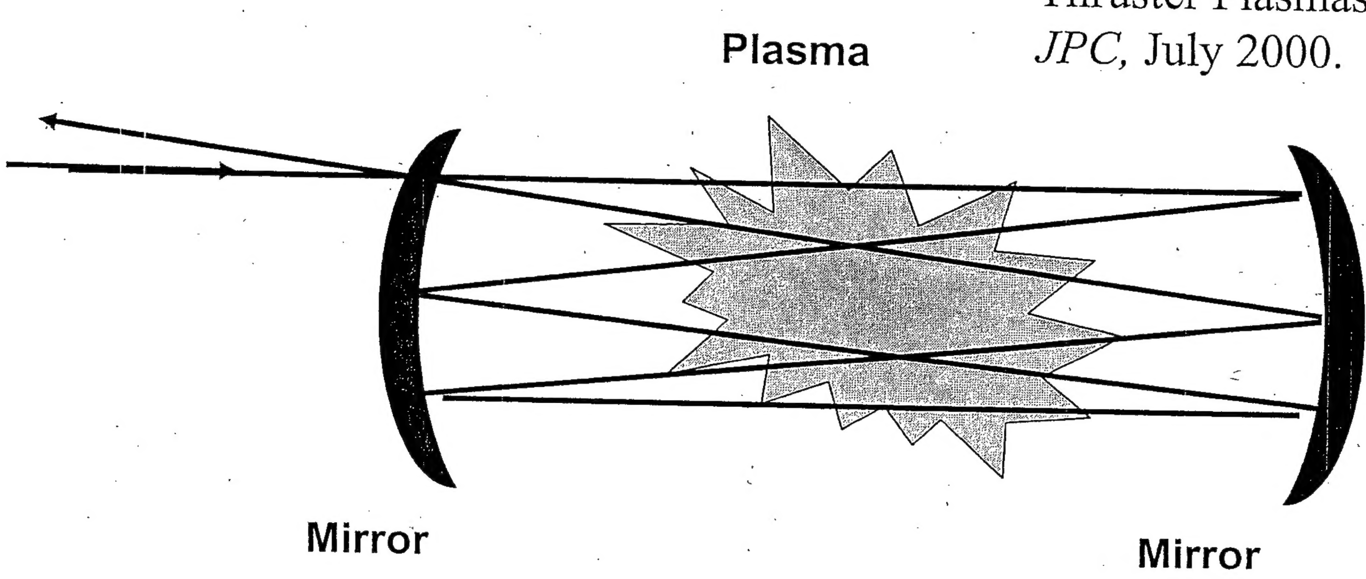
2002 HTPD
July 8-11, Madison, WI

Herriott Cell Concept

- Simple design requiring 2 concave mirrors and an off axis admission aperture
- Confine large number of laser reflections to increase interferometric path lengths

- Critical challenge is phase front maintenance for interferometry
  - Addressed:

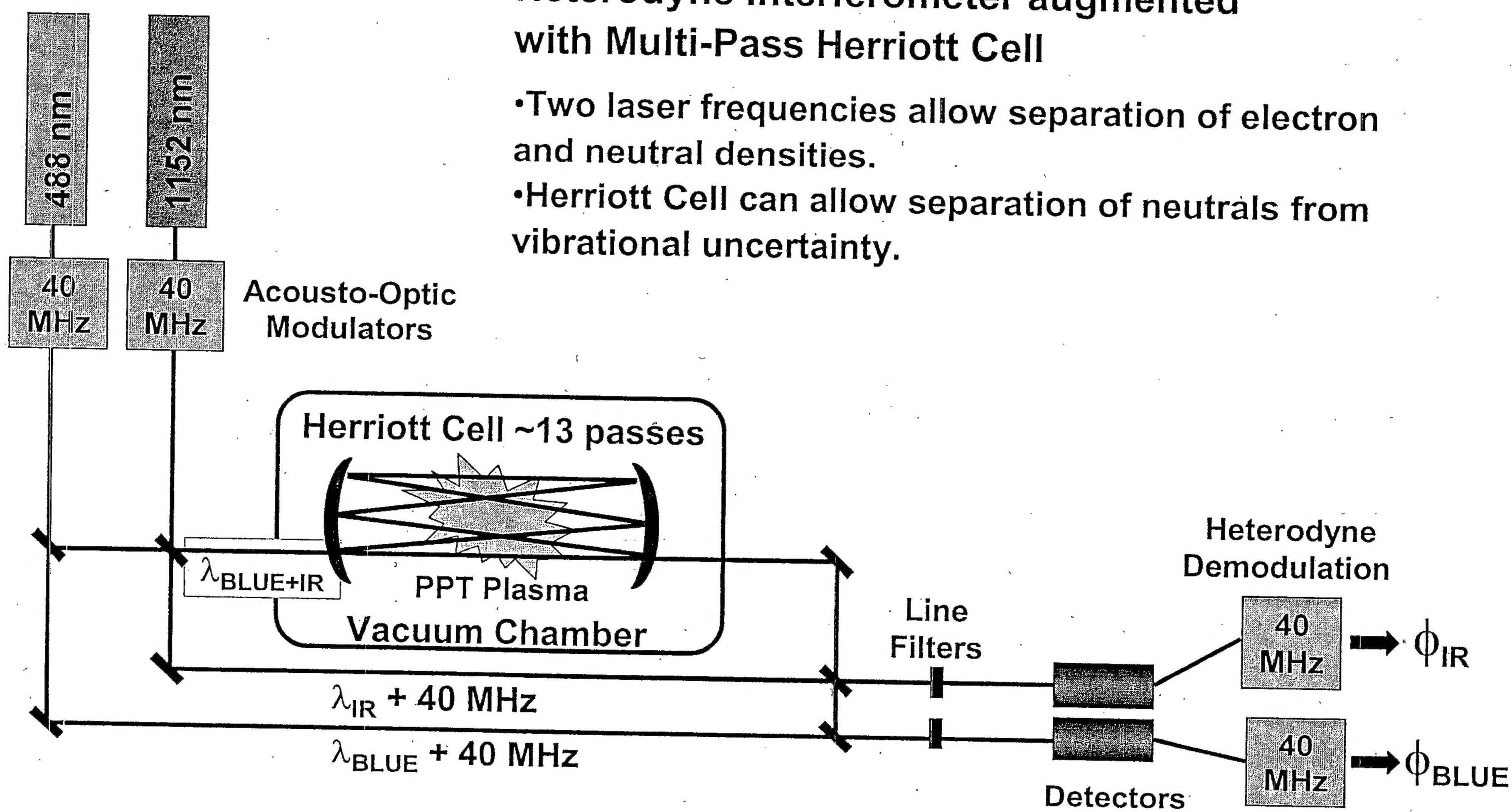
Antonsen, E. L., Burton, R. L., Engelman, S. F., Spanjers, G. G., "Herriott Cell Interferometer for Unsteady Density Measurements in Small Scale Length Thruster Plasmas," AIAA 2000-3431, *36th JPC,* July 2000.



Herriott Cell Interferometer Diagnostic Layout

Heterodyne Interferometer augmented with Multi-Pass Herriott Cell

- Two laser frequencies allow separation of electron and neutral densities.
- Herriott Cell can allow separation of neutrals from vibrational uncertainty.



Multiple Reflections Increase Instrument Resolution

$$\Delta\Phi_{TOTAL} = \Delta\Phi_{ELECTRONS} + \Delta\Phi_{NEUTRALS} + \Delta\Phi_{VIBRATIONS}$$

For multiple shots averaged:

Total Density Uncertainty

Shot-to-Shot Thruster Variation

$$\Delta n = \sqrt{\boxed{\Delta n_{vibs}^2} + \boxed{\Delta n_{PPT}^2}}$$

Vibrational Contribution (no dependence on N)

$$\boxed{\begin{aligned} \Delta\Phi_{ELECTRONS} &= C_e N \lambda \int n_e dl \\ \Delta\Phi_{NEUTRALS} &= \frac{C_n N}{\lambda} \int n_n dl \end{aligned}}$$

$$\boxed{\Delta\Phi_{VIBRATIONS} = \frac{C_v}{\lambda} \Delta L}$$

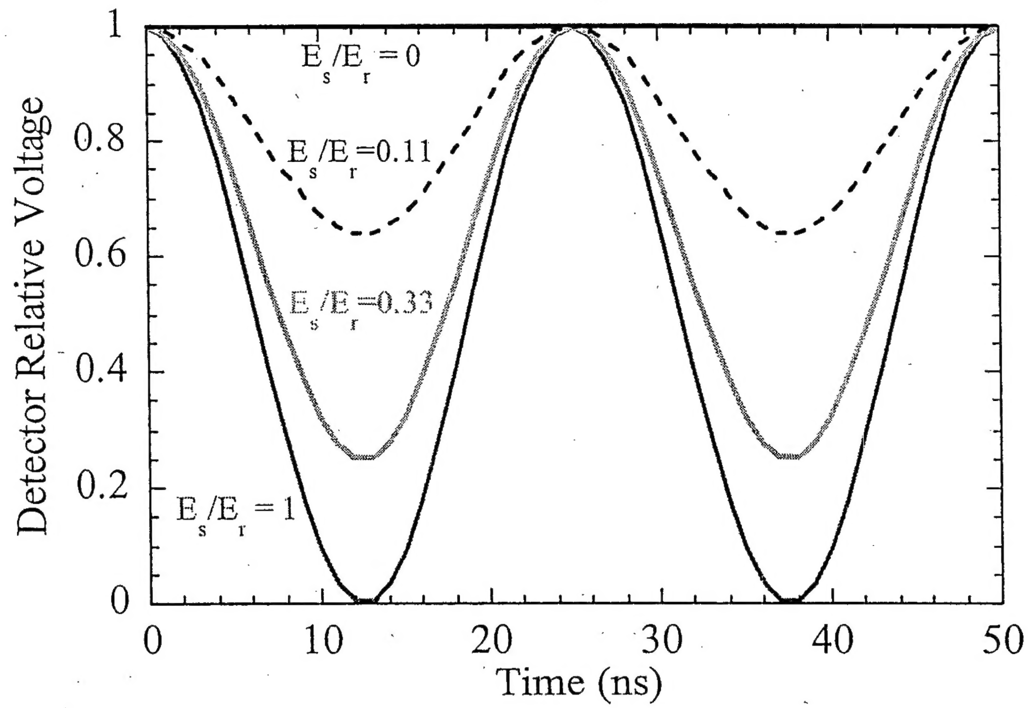
High number of passes increase sensitivity to electron and neutral phase shifts without increasing vibrational noise

Unbalanced Beam Intensities

$$V\left(\frac{E_S}{E_R}\right) \propto E_R^2\left[1 + \left(\frac{E_S}{E_R}\right)^2 + 2\left(\frac{E_S}{E_R}\right)\cos\left(\omega_A - \phi(t) - \gamma(x, y)\right)\right]$$

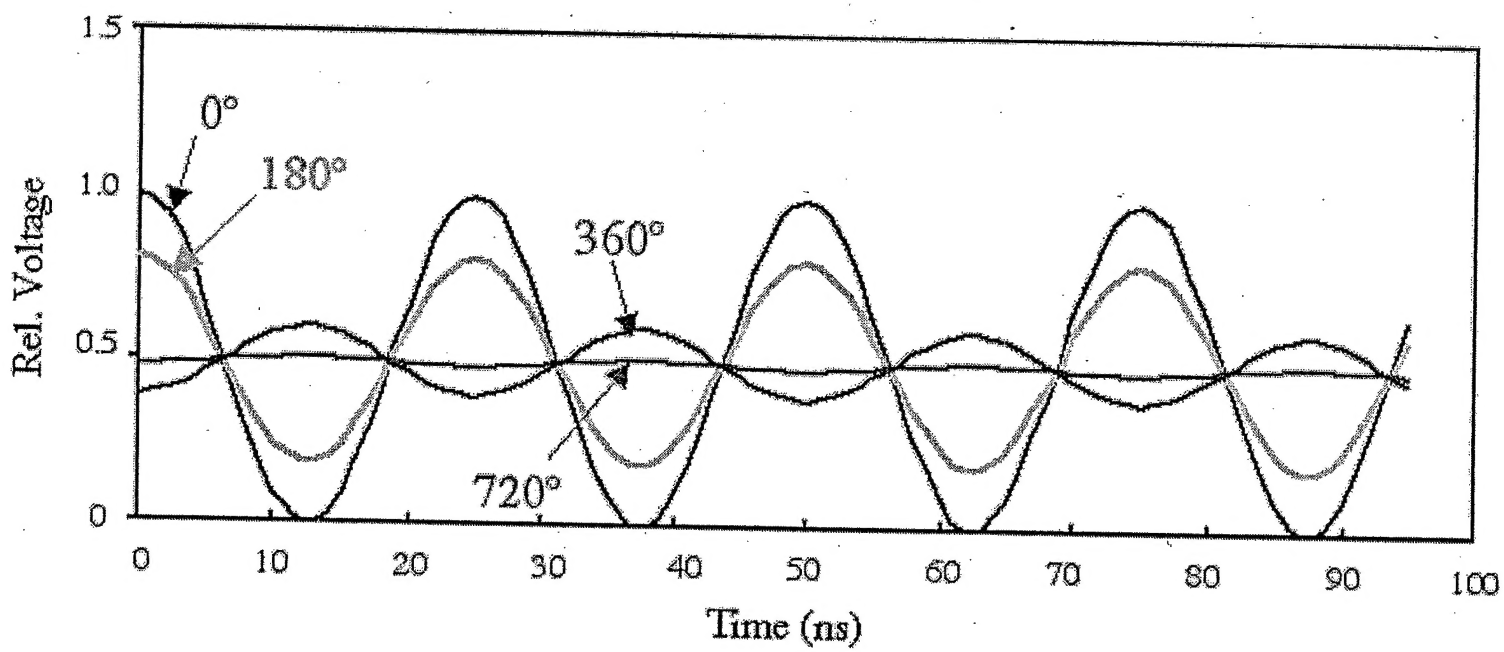
Effect of non-balanced intensities on the interferometer signal at the detector.

Relative intensities of the scene and reference beams are given above each trace.

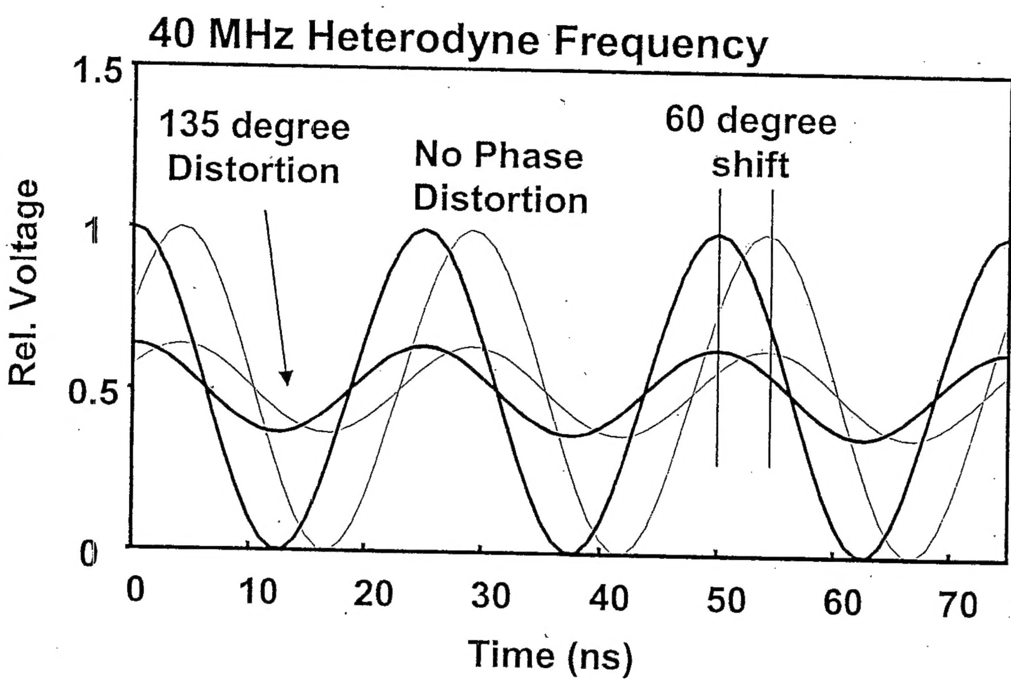


Phase Front Distortion Effects

- The trace labeled "0" corresponds to zero phase distortion, "180" corresponds to l/2 wavelength distortion, etc.
- In each case, the distortion is presumed linear in one direction across the beam diameter and the beam is presumed square.



Fundamental Limit to Ultimate Resolution



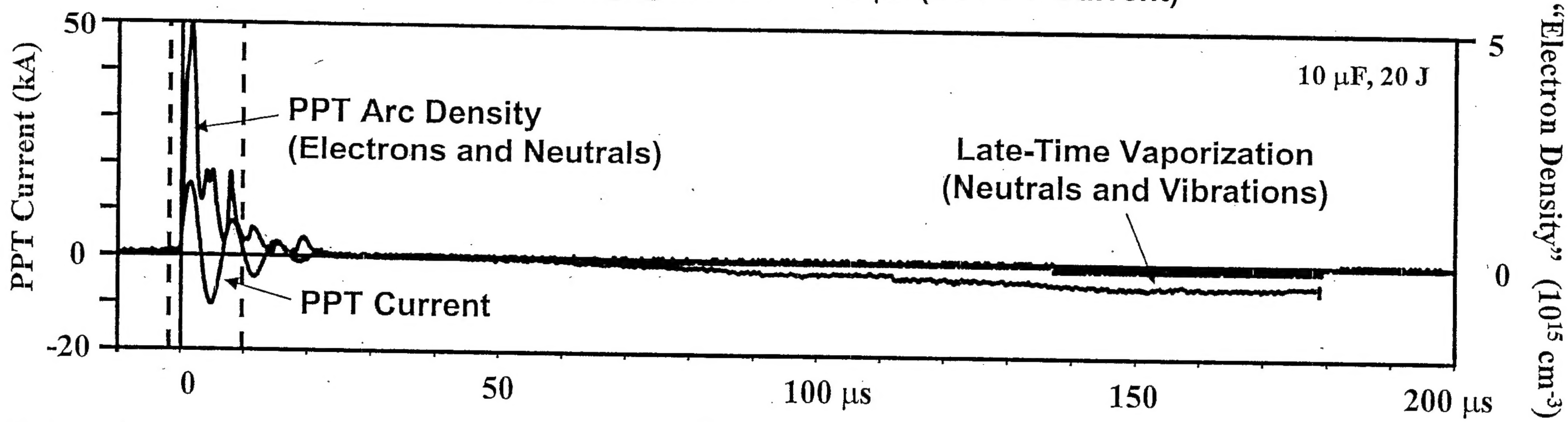
- Each Reflection degrades Phase Front of Scene Beam.
  - -Distorted phase front will appear as a net phase shift compared to undistorted case
- With plasma, distorted phase front shifts same magnitude as undistorted case. Thus, density is correctly measured.

- Loss of Phase Front appears as a decreased S/N.
- Does not introduce systematic error to measurement

Data Reduction

$$\Delta\Phi = 2.8\times10^{-15}\lambda\int n_e\,dl - \frac{3.9\times10^{-29}}{\lambda}\int n_n\,dl - \frac{2\pi\Delta l}{\lambda}$$

Assume: Vibrations Negligible for ~ 50 μs during discharge (f ~10 kHz)
Electron Density Negligible after ~50 μs (no PPT Current)



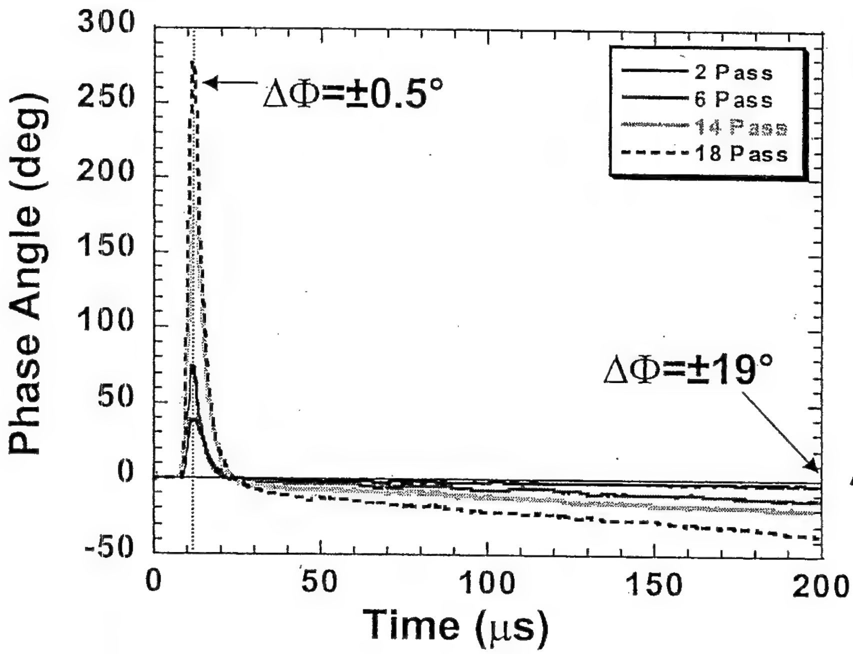
Vibrations Negligible
Only Electrons and
Neutrals Contribute

Electron Density Negligible
(no PPT Current)

Change Analysis
Technique

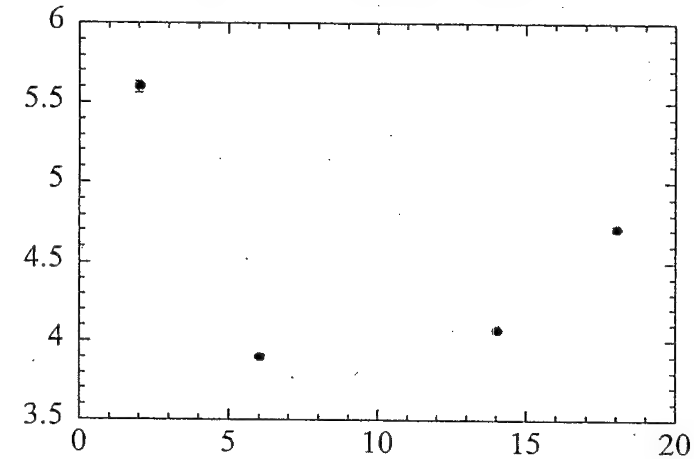
Experimental Results Show Increased Resolution

For single shots: Herriott Cell enables detection of neutrals by using 14-18 passes.

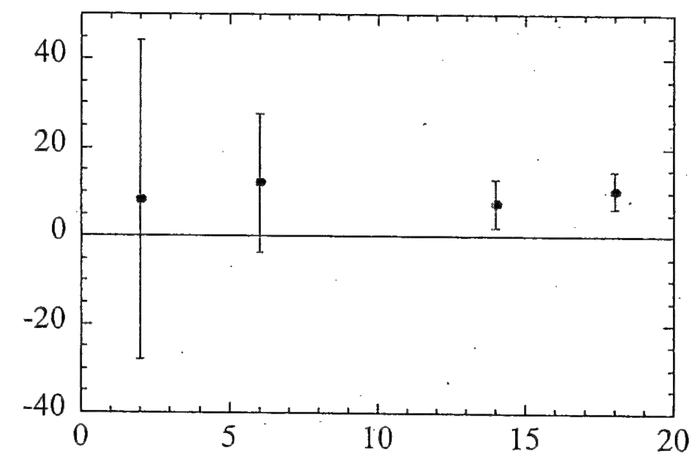


$$\Delta n = C\frac{\Delta\Phi}{N}$$

Electrons at 12 μs (10^{15} cm^{-3})

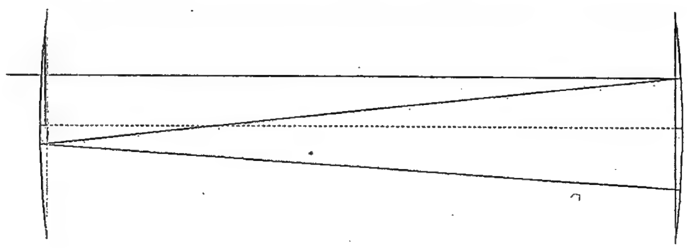


Neutrals at 200 μs (10^{15} cm^{-3})

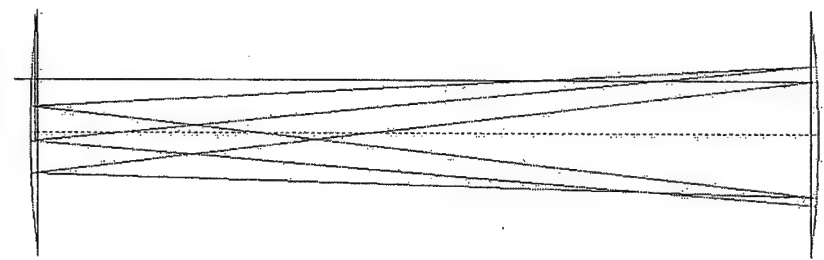


Number of Passes

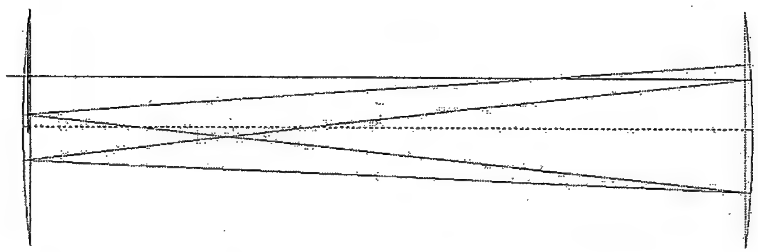
Retro-reflecting Configurations



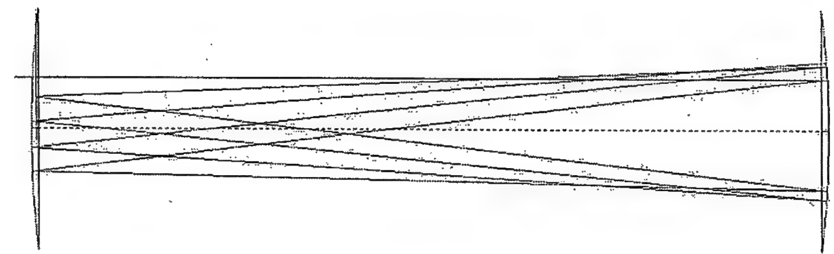
a.) 6 Pass, 140 mm Separation



c.) 14 Pass, 179 mm Separation



b.) 10 Pass, 168 mm Separation



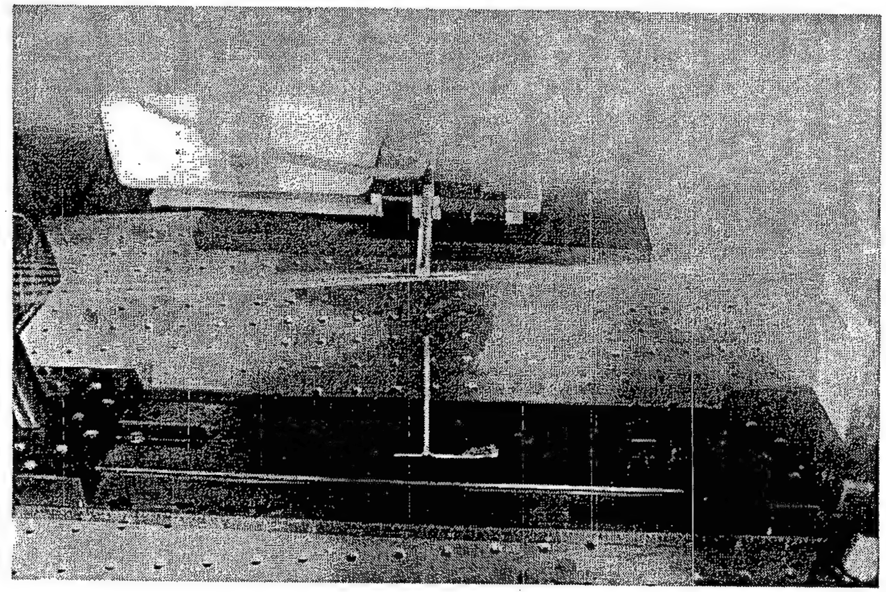
d.) 18 Pass, 184 mm Separation

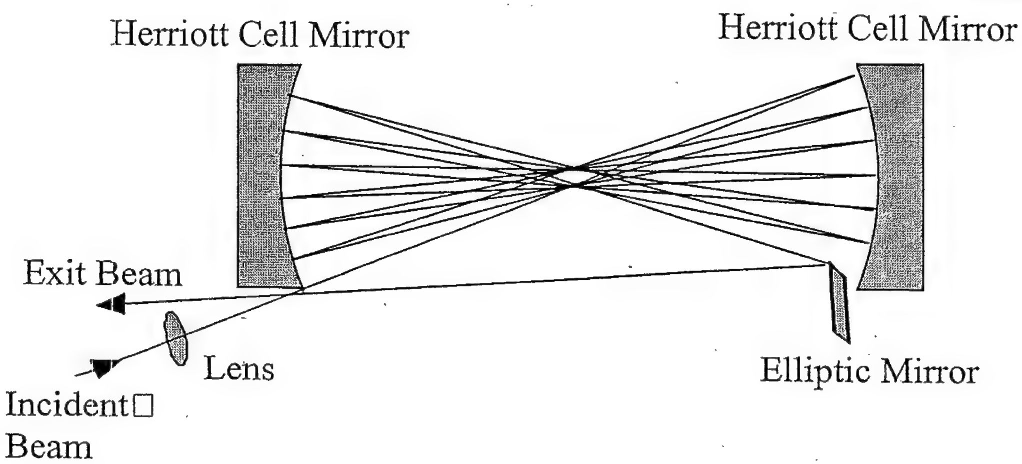
Various Retro-reflecting beam configurations using the Herriott Cell

Beam3 code by Stellar Software

Point Measurement Technique

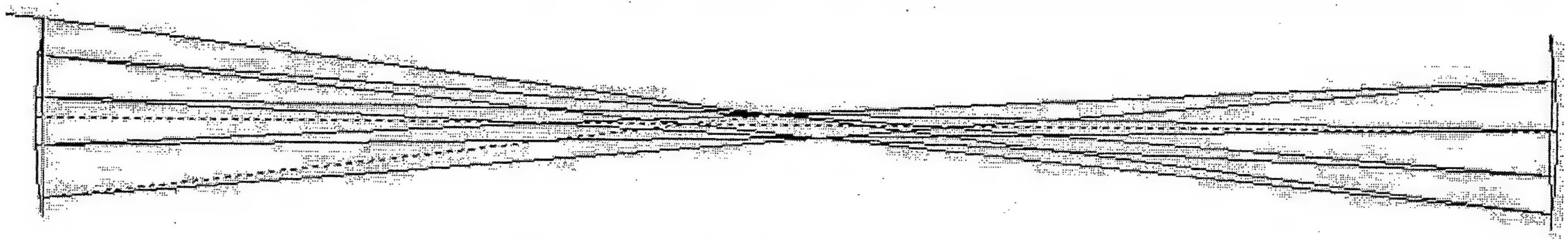
- Confine high number of beams to small area
- Increase signal-to-noise ratio



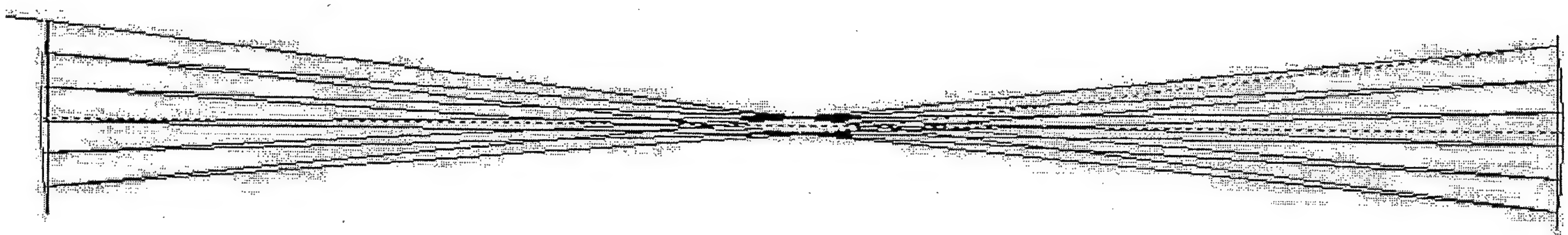


External optics required for point technique add some uncertainty

‘Point’ Configurations



a. 9 passes, right mirror tilt angle 2.86°

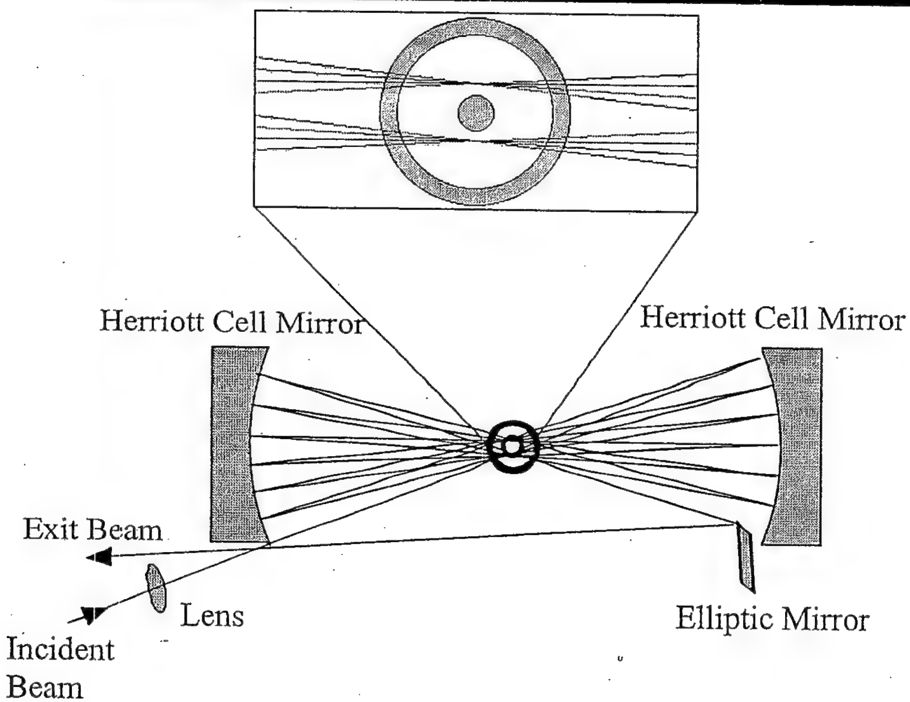


b. 13 passes, no mirror tilt

c. 16 passes, right mirror tilt angle -1.15°

Beam3 code by Stellar Software

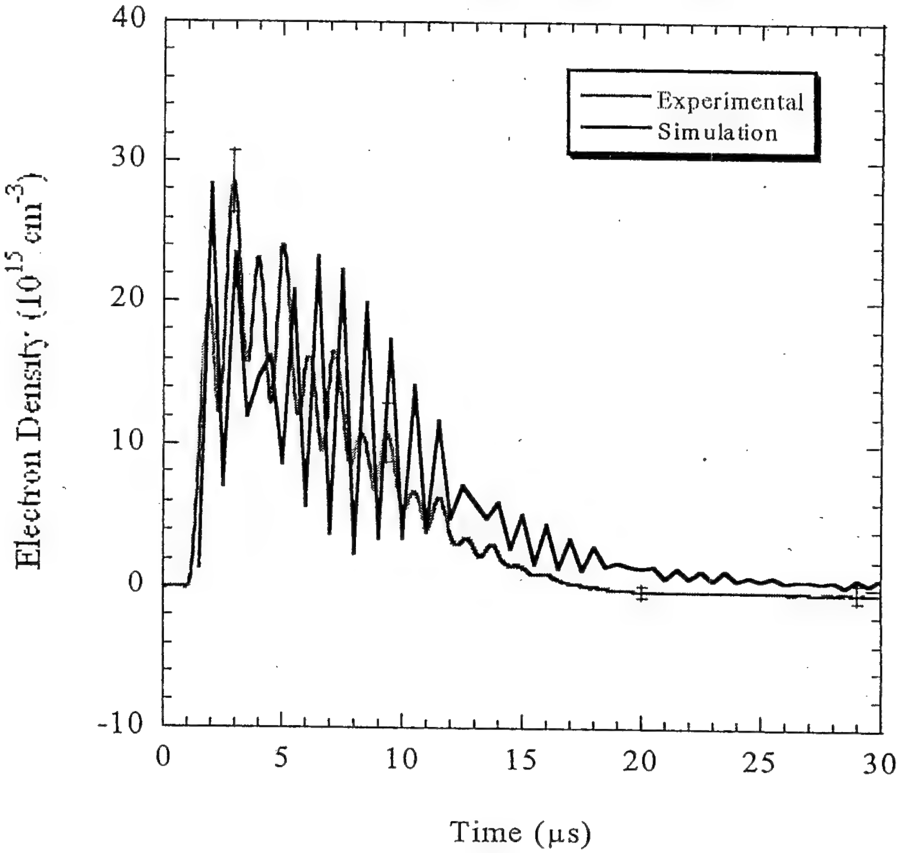
Herriott Cell Electron Density Measurement
1st Significant PPT Model Validation in 30 Years !



- Herriott Cell interferometer used to probe MicroPPT exhaust
- 'Point' measurement technique developed at AFRL allows measurements on small thruster geometries

Herriott Cell electron density measurements show strong agreement with model predictions

Model simulation compared with 13 pass Herriott Cell measurement ¼ in. DIA MicroPPT at 6.6 J

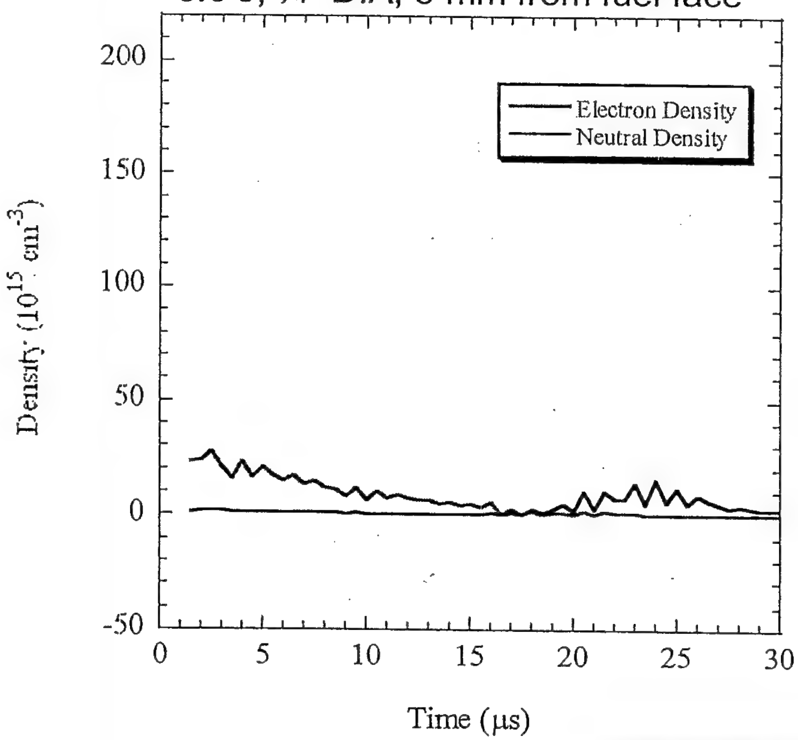


Neutral Density: Model and Experiment

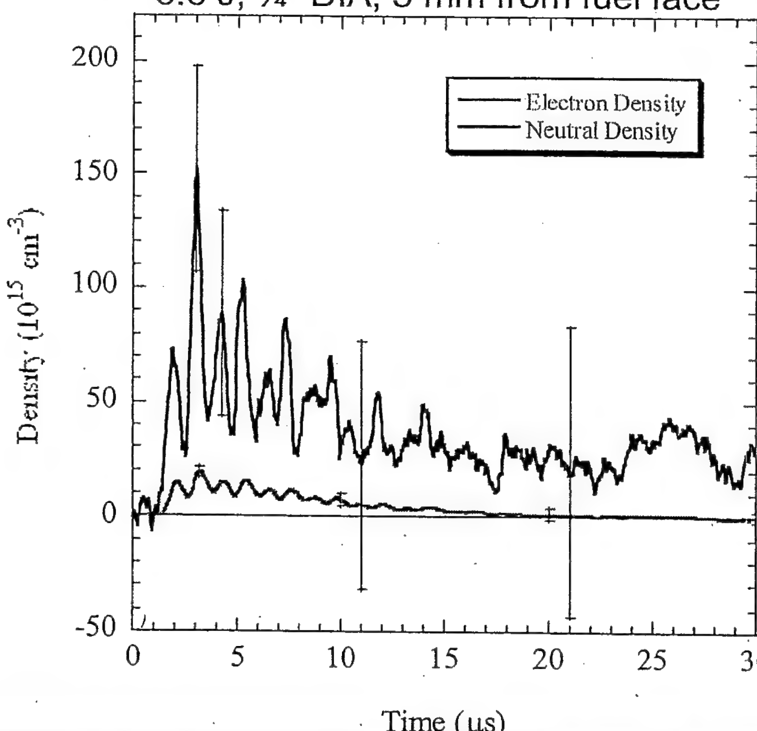
Plasma equilibrium assumption may be source of neutral density disagreement during the discharge between model and experiment

Neutral density determined by heat flux from plasma – surface temperature measurement can help correct the model

Simulated electron and neutral density
6.6 J, ¼" DIA, 5 mm from fuel face



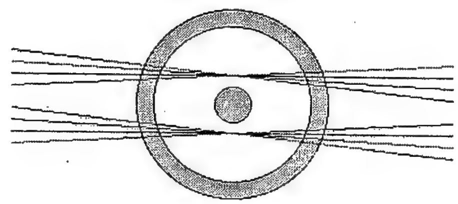
Measured electron and neutral density
6.6 J, ¼" DIA, 5 mm from fuel face



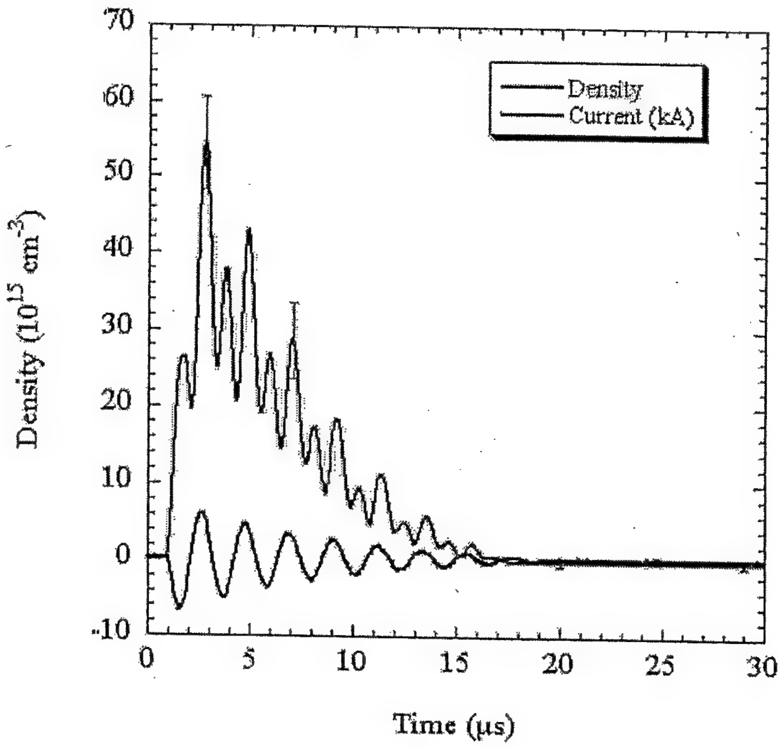
2-color
2-pass
Interferometer
Measurement

New Diagnostic Development Needed to Check Model Sensitivity to Surface Temperature

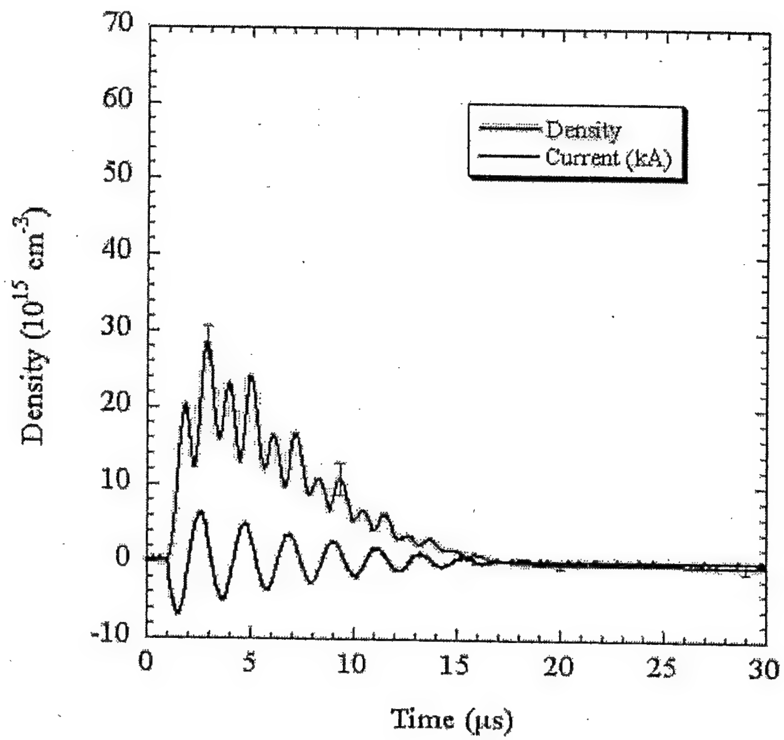
Electron Density Results



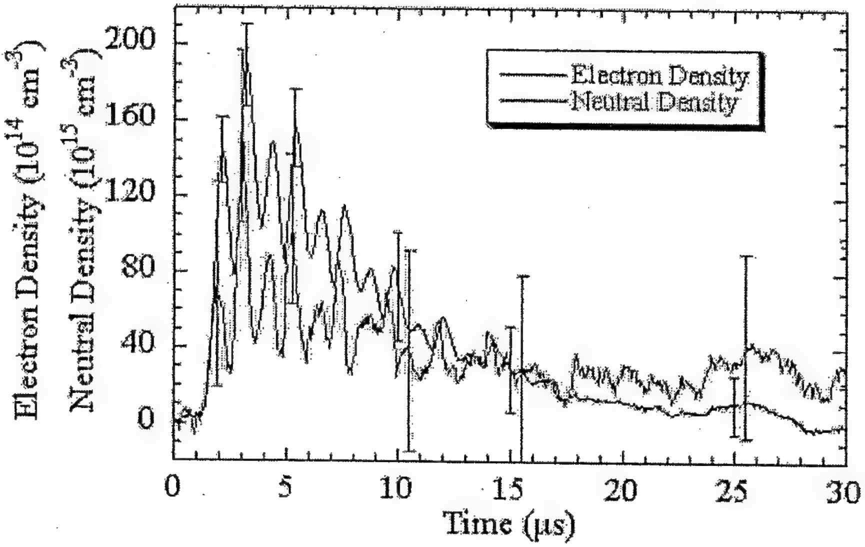
1 mm from fuel face
13 passes, 6.6 J



5 mm from fuel face
13 passes, 6.6 J

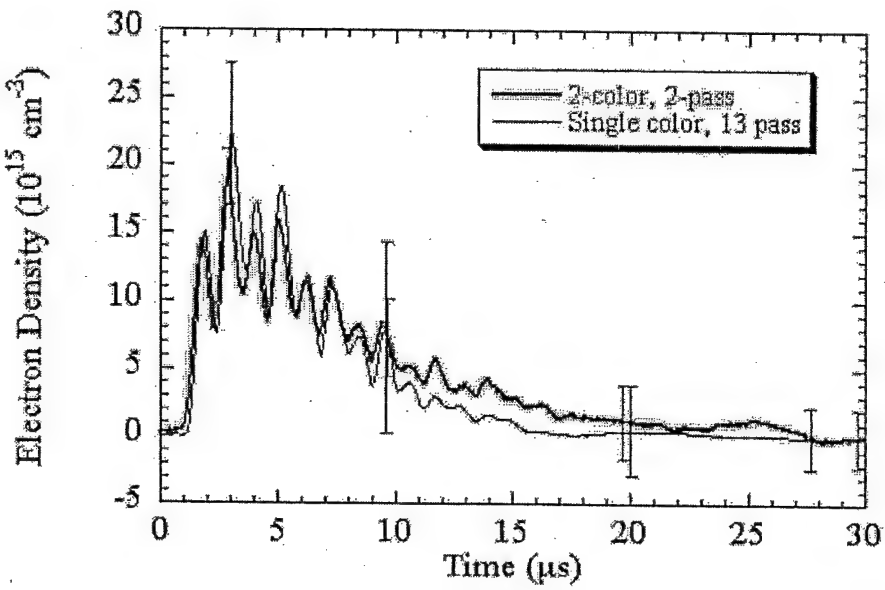


Two-Color Data



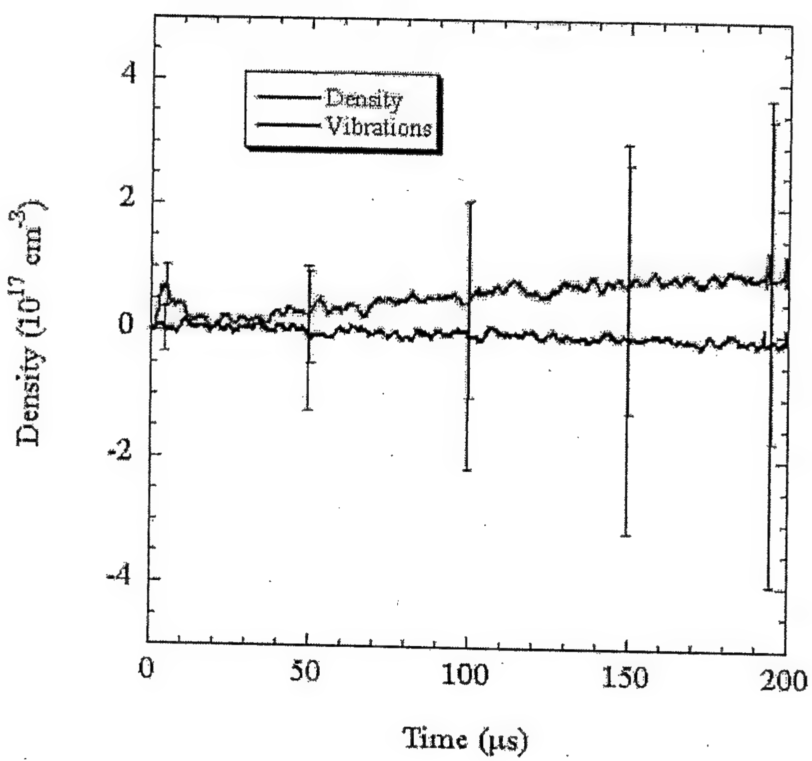
- Two color separation of electrons and neutrals
- Allows calculation of ionization fraction

Comparison of two-color data with 13 passes Herriott Cell show good agreement

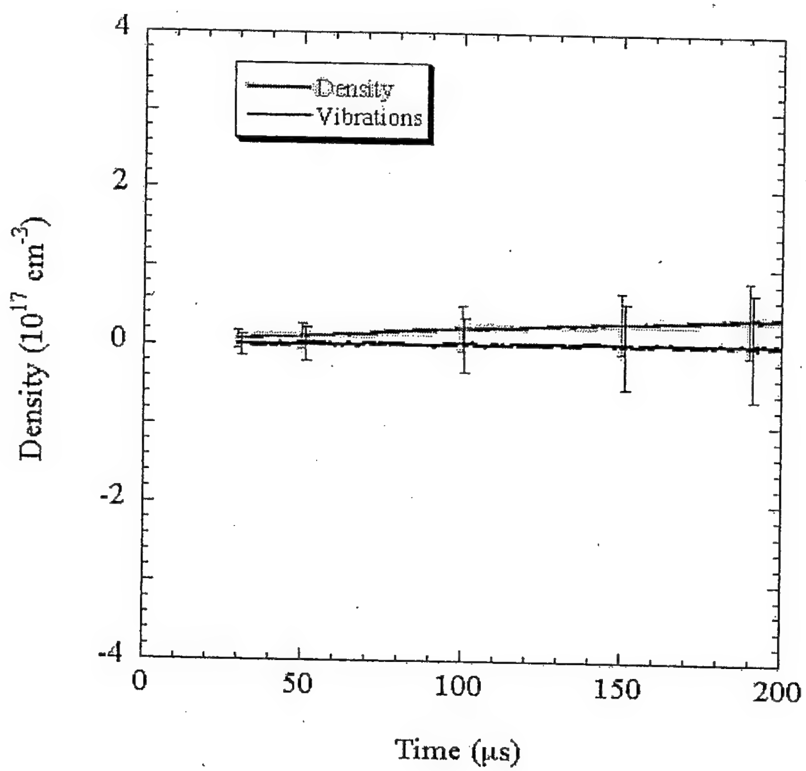


Neutral Density Uncertainty

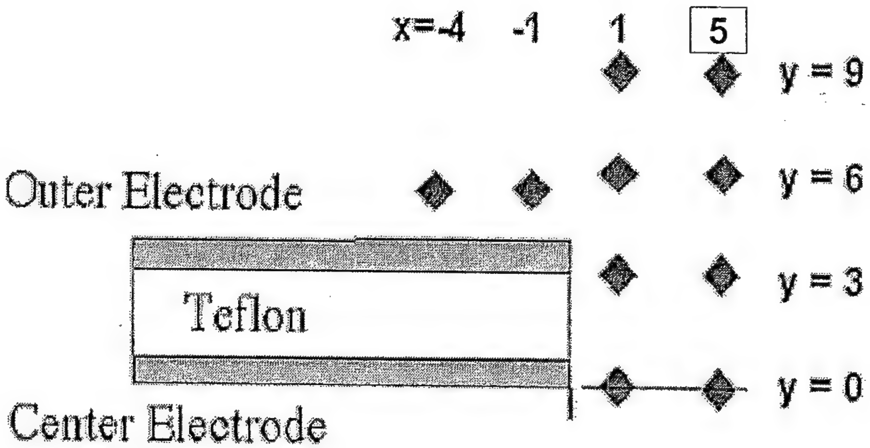
Two-color, two-pass electrons and neutrals separated but large uncertainty

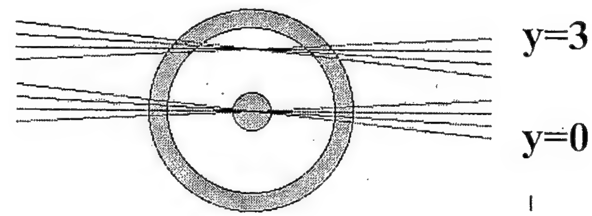


13 passes in Herriott Cell show significant decrease in uncertainty

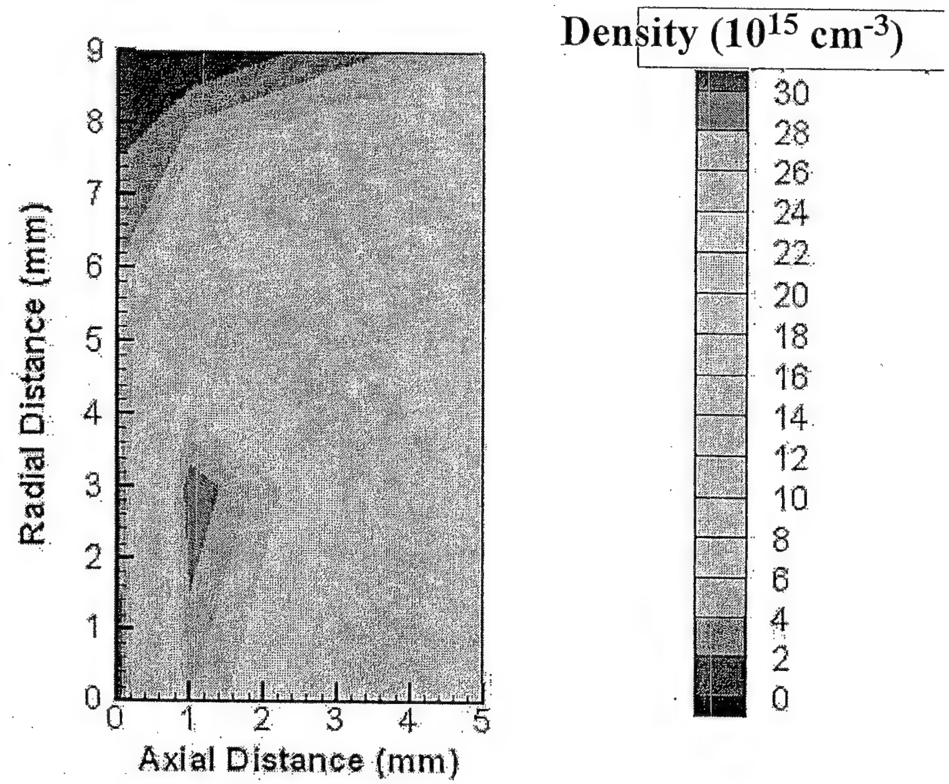


Peak Electron Density Results

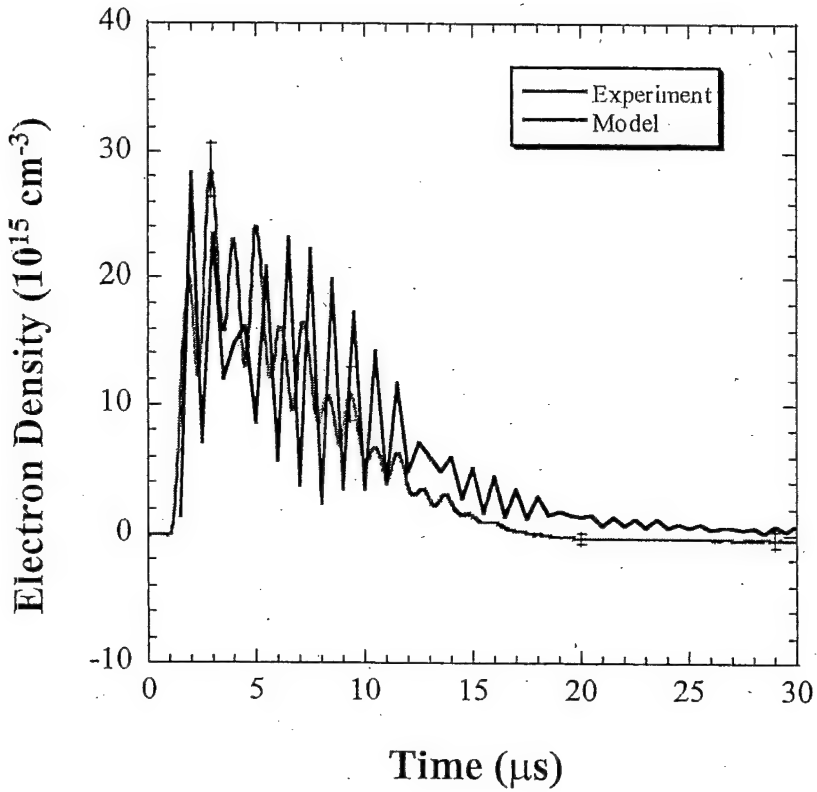




- Peak electron density ($t=2\mu s$)
- Assume ($x=1$, $y=0$) has zero density, count in by focal points



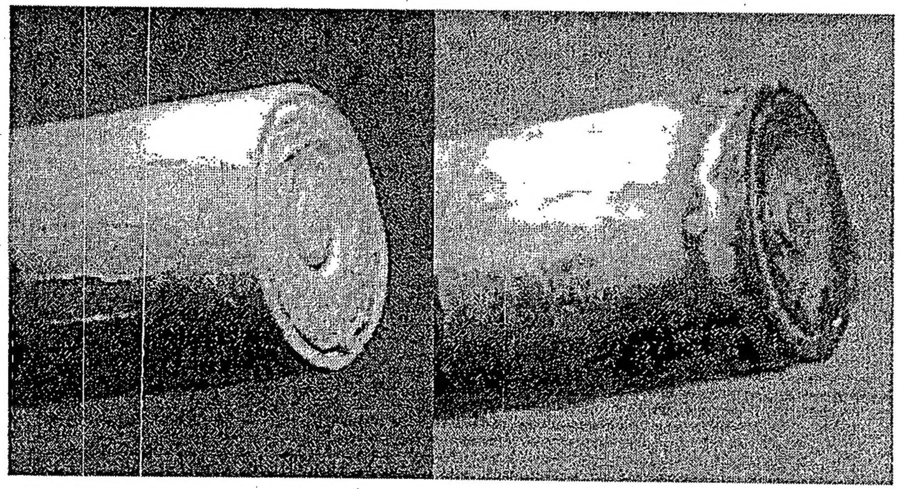
Direct Comparison

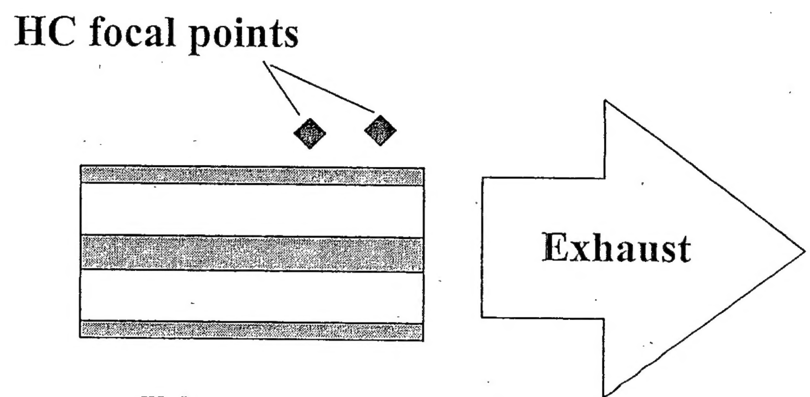


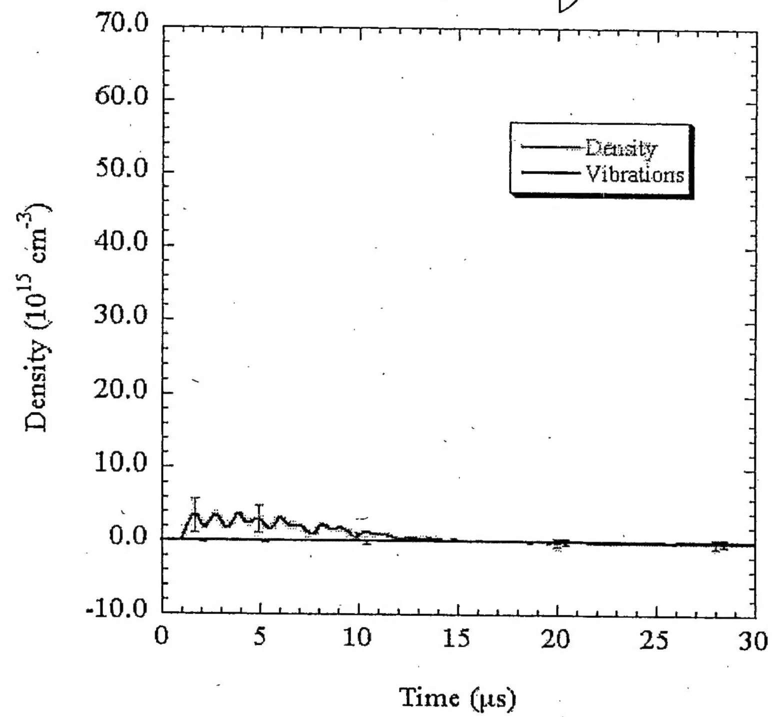
- Simulation uses measured current waveform as energy input
- 6.35 mm diameter, 6.6 J
- Measurement made 5 mm from fuel face
- Keidar and Boyd Model presented in IEPC 01-155

delete or
replace
(releasability questioned))

External Density Measurements



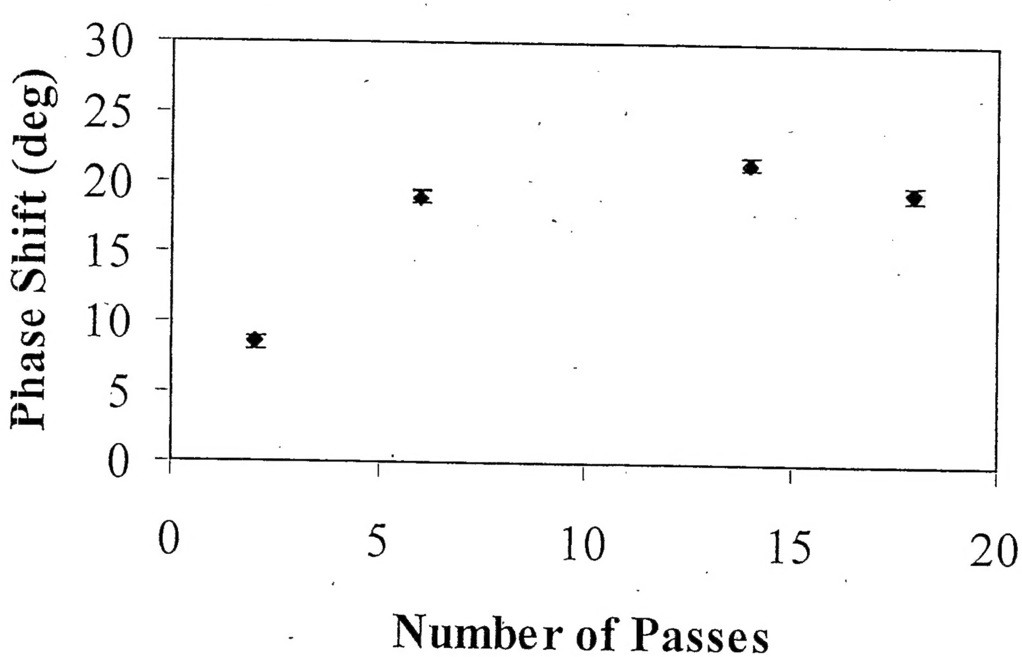




Barium Hydroxide coating on MicroPPT

- Shows recession of 1-3 mm from from thruster exit plane
- Corresponding external electron density measurements ($4 \pm 2 \times 10^{15}$ cm^{-3})

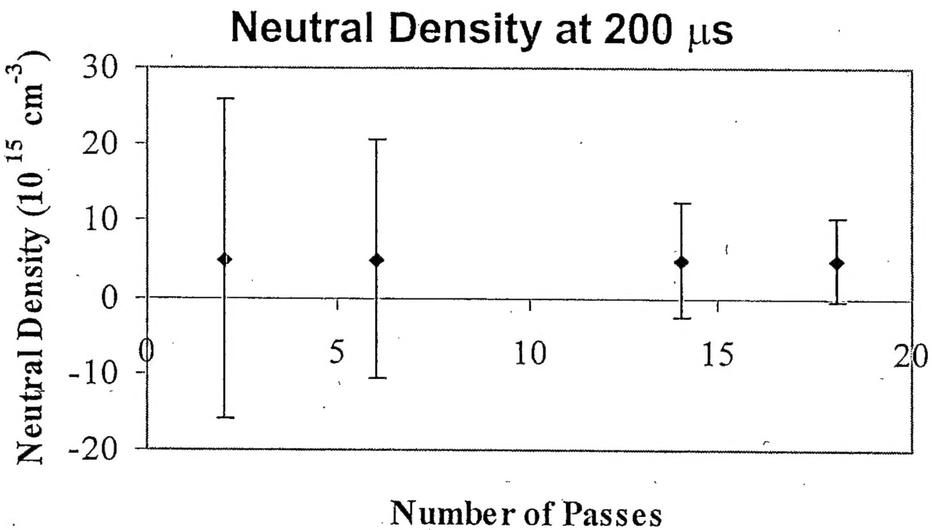
Vibrational Noise Effects

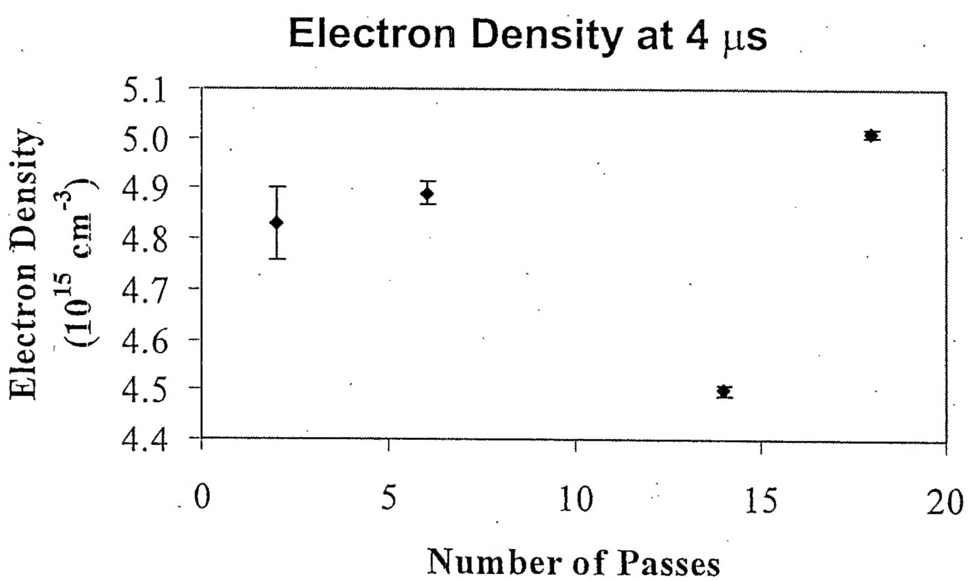


- No Plasma Present
- Data points average of 20 plasma firings
- Error bars due to 0.5° detector limitation

Effect of Multiple Reflections

Data Taken at 2, 6, 14, and 18 reflections on UIUC PPT-4





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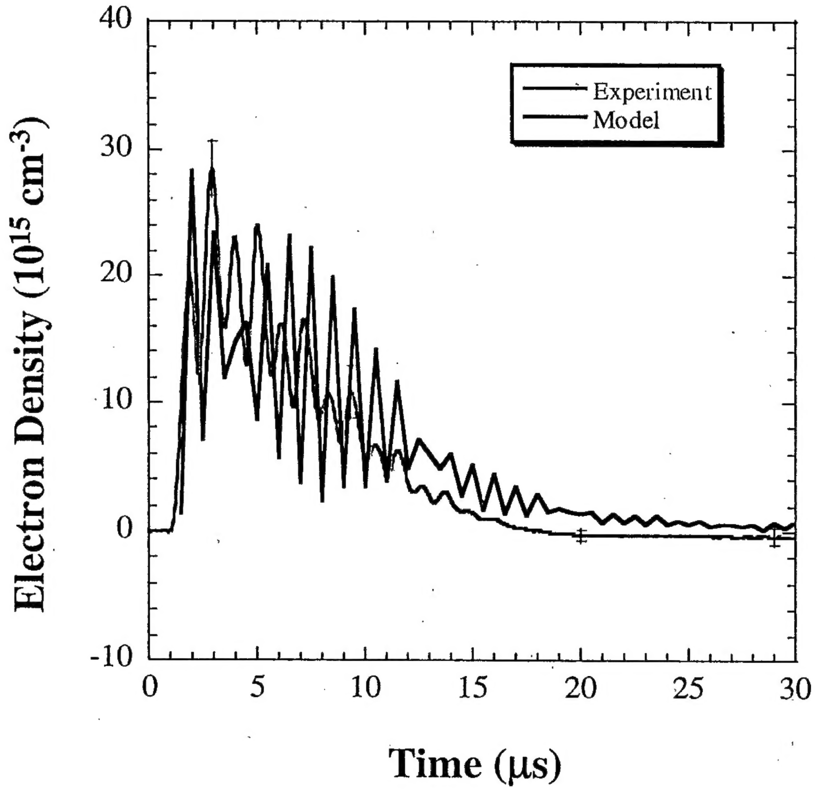

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- Measurement made 5 mm from fuel face
- Keidar and Boyd Modeling effort (in submission to JPP)